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Longitudinal-Mode Combustion Instabilities: Modeling and Experiments

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ABSTRACT

Combustion instabilities can lead to increased development time and cost for aeroengine gas turbines. This problem has been evident in the development of very-low emissions stationary gas turbines, and will likely be encountered in the newer, more aggressive aeroengine designs. In order to minimize development time and cost, it is imperative that potential combustion dynamics issues be resolved using analyses and smaller-scale experimentation. This paper discusses a methodology through which a problem in a full-scale engine was replicated in a single-nozzle laboratory combustor. Specifically, this approach is valid for longitudinal and "bulk" mode combustion instabilities. An explanation and partial validation of the acoustic analyses that were used to achieve this replication are also included. This approach yields a testbed for the diagnosis of combustion dynamics problems and for their solution through passive and active control techniques.

NOMENCLATURE

A – cross-sectional area
e_0 – total energy
H_0 – total enthalpy
$\dot{m}_s$ – mass source flow
$\dot{q}_s$ – heat release
T – temperature
γ – ratio of specific heats
ζ – loss coefficient
D_h – hydraulic diameter
f – friction factor
X – axial coordinate
P – pressure
t – time
u – velocity
ρ – density

INTRODUCTION

Aggressive performance and emissions goals for aeroengine gas turbine combustors have led to the development of combustor concepts that may operate closer to static and dynamic stability boundaries. Lean, direct-injection combustors under development share many features with the lean, premixed combustors used in stationary gas turbines, in which combustion instabilities are widely observed.

In order to minimize development costs and time, it is critical to possess the ability to evaluate the dynamic behavior of a combustor design during the component-development phase, thereby mitigating the need for expensive full-scale engine testing late in the development cycle. Solutions to combustion instability problems, such as active and passive controls, can be evaluated and developed more quickly in a laboratory-scale experiment, enabling a faster transition of technology into production engines.

Laboratory- or component-scale testing of developmental combustor concepts is standard practice in the aircraft gas-turbine industry, using single-nozzle flame tubes, single- and multi-nozzle sectors and full-annular combustor rigs. The gas turbine community has developed an experience base regarding the fidelity with which such test rigs must replicate engine design details in order to characterize the emissions and operability characteristics of engine combustors. At this time there is no proven methodology for replicating engine-scale combustor dynamics in laboratory-scale rigs. The challenge in designing laboratory-scale combustion dynamics experiments is to replicate the engine dynamic environment in as simple (low-cost) an apparatus as possible. Recent published work suggests that bulk mode and longitudinal mode instabilities can be replicated in single-nozzle rigs. Cohen et al. (1998) and Hibshman, et al. (1999) performed active instability control experiments in single-nozzle and sector combustors that reproduced a bulk-mode instability observed in a lean, premixed industrial combustor. Paschereit et al. (1998) have developed a sub-scale combustor in which the boundary conditions at the inlet and exit ends can be varied to impose a desired acoustic mode. No relevant work has been published on replication of tangential modes in multi-nozzle sector or configurations other than full annular combustors.

While the aforementioned investigators have shown that it is possible to create a realistic, laboratory-scale combustion dynamics experiment, the scaling processes through which these experiments can be designed have not been described with sufficient specificity to allow the methodology to be adopted by the technical community at large. In order for the results of sub-scale experiments to be useful to engine designers, there must be a system in place to translate those results to engine-scale. This paper discusses such a process, involving the following steps:

1. Analysis of dynamic data from the subject engine to determine characteristics of instability: frequency, amplitude, and sensitivity to changes in hardware configuration and operating conditions.

2. Acoustic analysis of the engine in order to determine acoustic modes associated with instability.

3. Conceptual design of a single-nozzle experiment, reproducing the engine's acoustic environment and replicating the relevant dynamic processes, as determined in steps 1 and 2.

4. Acoustic analysis of sub-scale experiment to determine its fundamental acoustic modes in order to confirm similarity with those observed in the engine.

5. Test of the finalized laboratory-scale experiment and comparison of data to analyses and engine data.

This paper presents the application of this process to an example problem, beginning with the analysis of an engine-traceable instability and culminating in the comparison of the lab-scale results to those from the engine

ENGINE PROBLEM ANALYSIS

The sample problem that was selected for this effort was a combustion instability that was observed during the development phase of a high-performance aero-engine that employed a full-annular combustor with 24 fuel nozzles. The frequency of the instability varied from about 420 Hz at low-power conditions to about 580 Hz at high-power conditions, as shown in Fig. 1. At a mid-power operating point, corresponding to that used for the analytical phase of this study, the frequency of the instability was 525 Hz. The magnitude of the pressure oscillations resulting from the instability were sufficient to cause unacceptable vibratory stresses in the turbine component of the engine

Passive means of reducing the magnitude of the pressure oscillations were developed during engine testing. This series of tests was able to detect a notable difference in the pressure oscillation magnitude when the fuel nozzle /air swirler design was changed. This led to the conclusion that the nozzle/swirler were important contributors to the instability mechanism.

To test this conclusion, a limited series of non-reacting experiments were conducted (Anderson, et al., 1998) to determine the acoustic and fluid mechanic response characteristics of the air swirlers that were used in the engine tests. The aim of these experiments was to measure differences in the responses of the air swirler/fuel injector designs that might explain their behavior in engine tests. It was found that the air swirlers associated with the largest pressure oscillations exhibited a preferential response to air flow perturbations in the frequency range between 300 Hz and 500 Hz. Air swirlers that performed better in the engine did not exhibit this phenomenon in the non-reacting tests.

While fast-response combustor pressure data were acquired during the engine tests, they were acquired at a limited number of locations. For this reason, it was difficult to draw any significant conclusions about the nature of the instability purely from the engine data. The analyses described in the next section of this paper were used to augment and interpret the engine data. The combination of the engine data, the acoustic analyses and the non-reacting swirler/injector characterization provided the basis for replicating the problem in a single-nozzle combustor rig.

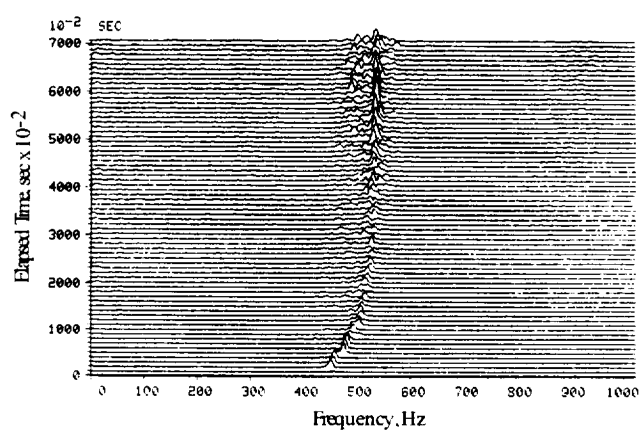

Figure 1. "Waterfall" plot of combustor pressure spectra from an engine test, showing evolution of the instability during an acceleration event.

Analysis of Engine Acoustics

A quasi-1D unsteady Euler analysis (Wake et al., 1996) was used to predict the bulk and longitudinal modes of the engine combustor. The one-dimensional Euler equations were solved with area variation and modeled source terms to account for mass addition, heat addition and pressure losses. The resonant acoustic frequencies of the combustor were determined by solving for the unsteady time-accurate response of the system and monitoring the fluctuating pressure at a specified location. The analysis can be used to examine the sensitivity of the frequency and pressure amplitude to system parameters such as physical dimensions, temperature distribution, Mach number, flow rate and pressure drop. The solver was first used to compute the steady-state results, and then unsteady results were obtained by forcing the system. Forcing was accomplished by adding an unsteady component to the heat release. Two types of forcing signals were used: 1) broadband white-noise distributed forcing, and 2) swept sine forcing at a fixed frequency. The magnitude of the heat release forcing was 10% of the mean heat release rate. The resulting pressure response indicated the frequency dependence of the combustion system.

The governing equations are the unsteady quasi one-dimensional Euler equations with area variation and source terms. The source terms are used to add mass, heat and momentum losses. The equations are normalized by the upstream total quantities. The differential equations employed are:

$$\frac{\partial(\rho A)}{\partial t} + \frac{\partial \rho u A}{\partial x} = \frac{\partial \dot{m}_s}{\partial x}$$

$$\frac{\partial(\rho u A)}{\partial t} + \frac{\partial(\rho u^2 A + PA)}{\partial x} - P\frac{\partial A}{\partial x} = -f_\mu - f_P$$

$$\frac{\partial(\rho e_0 A)}{\partial t} + \frac{\partial(\rho u H_0 A)}{\partial x} = \frac{\partial(\dot{m}_s H_0 + \dot{q}_s)}{\partial x}$$

The pressure, total energy and enthalpy are given by:

$$P = \frac{\rho T}{\gamma}$$

$$e_0 = \frac{T}{\gamma(\gamma-1)} + \frac{u^2}{2}$$

$$H_0 = \frac{T}{(\gamma-1)} + \frac{u^2}{2}$$

$$\gamma = \gamma(T)$$

The pressure loss terms in the momentum equation are given by:

$$f_\mu = \rho u|u|\frac{2fA}{D_h}$$

$$f_P = \frac{\partial(\frac{1}{2}\rho u|u|A\zeta)}{\partial x} = \frac{\partial(\frac{1}{2}\Delta P_{loss}A)}{\partial x}$$

where f_μ is the pressure loss due to skin friction and f_P is used to lump pressure losses due to sudden expansions, and perforated plates.

It should be recognized that this analysis is useful for its intended role of the determination of acoustic modes. The analysis does not attempt to incorporate the physics of the interaction of the fluid mechanics/acoustics with the heat release (effects of flame shape variation, local fuel/air variations, etc.) and therefore is not capable of predicting the *absolute magnitude* of the pressure response. The approach demonstrated in this paper will show that it is, however, a satisfactory tool for evaluating test rig acoustic characteristics for different combustion dynamics experiments.

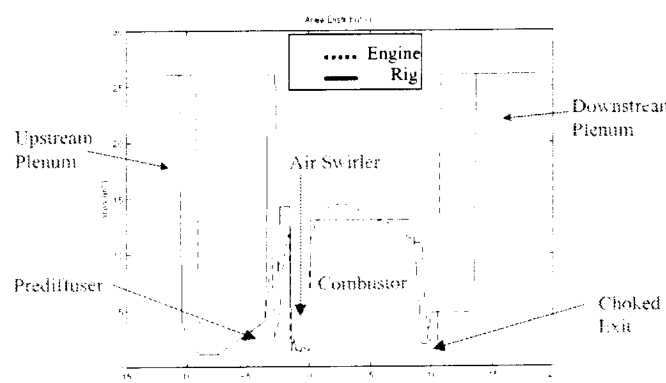

Figure 2. Cross-sectional area vs. axial position for quasi-1D Euler model.

Quasi-1D Euler calculations were conducted for the engine configuration at an intermediate operating condition: T3 = 771°F (684K) and P3 = 200 psia (1.2 MPa). The engine geometry was converted into a one-dimensional description of area vs. axial position as shown by the dashed line in Fig. 2, which shows the distributions for both the engine and the rig (to be discussed later). The geometry used included an inlet plenum, the engine prediffuser, diffuser plenum, the cowl or hood, the swirler, the combustor liner and turbine vanes. The combustor lies between x = 0 and 9.25 in. Beyond the turbine vane exit, the area was expanded rapidly to create a plenum dump. The boundary conditions used were constant total pressure at the inlet plenum and constant static pressure at the exit plenum.

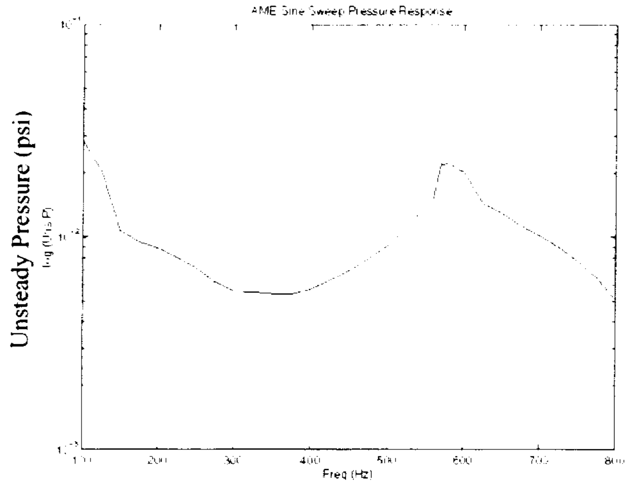

Figure 3. Computed power spectrum of combustor pressure for engine configuration with 100-800Hz sine-sweep forcing.

The acoustic response of the system was obtained by swept-sine forcing of the entire heat release distribution. The fluctuation levels imposed on the heat release were 10% of the mean. The unsteady pressure amplitude at the x = 3 in. location in the combustor (3 in. downstream of the combustor dump plane) was used to determine the pressure response. This location was chosen because it roughly aligned with the centroid of the presumed heat-release distribution. The swept-sine response is shown in Fig. 3 and indicates a resonance at approximately 575 Hz. The width of the amplitude response peak indicates a large amount of damping. However, the width of the response also indicates a broad range of frequencies over which the system may be susceptible to combustion instability.

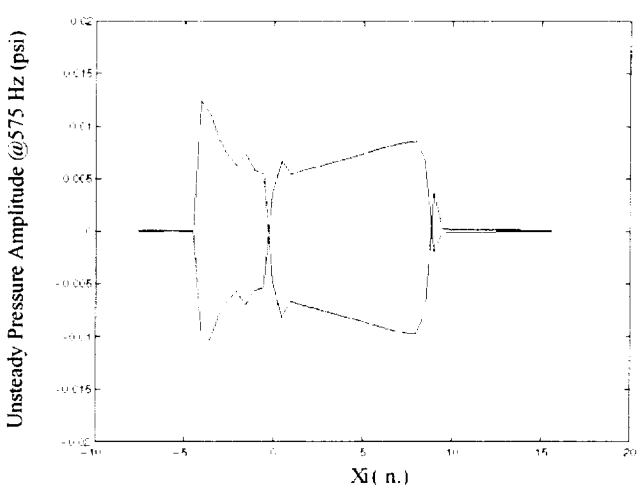

Figure 4. Computed pressure mode shape for 575 Hz mode for the engine configuration at evaluation point conditions.

These results indicated a longitudinal mode in the combustor near 575 Hz, near the observed frequency of about 525 Hz. The pressure mode shape for this mode is shown in Fig. 4. The mode represents a full-wave solution to the system equations with zero unsteady pressure specified at each end. Given the high impedance at each end due to the high Mach number boundaries, the mode shape can also be interpreted as a half-wave across the diffuser-combustor domain with closed ends. Note there is a pressure node apparent at the air swirler/fuel injector (x=0). The calculated fluctuating pressure in the diffuser was 180 deg. out of phase from the pressure in the combustor. It is believed that this was the basic acoustic mode that occurred in the engine configuration instability. Although tangential acoustic modes exist in the full-annular engine combustor, analysis of the engine data and two-dimensional Euler results have indicated that they are not associated with the observed instability.

EXPERIMENT DESIGN

Test Apparatus Features

Based on prior experience (Peracchio et al., 1998) the test rig design approach incorporated the following guidelines:

A. *Use of full-scale fuel preparation sub-components (fuel nozzles, air swirlers)*

   Prior evaluations (Anderson et al., 1998) indicated that the prototype injector/swirler exhibited an enhanced response near the 500 Hz frequency observed in the engine data so it was important to utilize that precise design. While reduced-size hardware may be of interest in order to minimize facility requirements, this approach was not taken, due to the introduction of uncertainties associated with reduced-scale flows.

B. *Reproduction of the longitudinal acoustic behavior*

   The critical elements in this regard were the combustor, the diffuser, the pre-diffuser, and the cowl (hood) which guided the diffuser air to the fuel nozzle. Table 1 shows a comparison of the geometric features of the annular engine burner with those of the rig. Here, "shroud" refers to the region between the combustor liner and combustor casing. Cross-sectional areas were chosen to replicate associated volumes and expansion/contraction ratios.

C. *Acoustic isolation of the combustor from facility air piping*

   A venturi was used to choke and meter the inlet air flow. Since the isolation provided by the sonic throat condition was desired over a range of conditions, the venturi was designed to be underexpanded, resulting in a normal shock at a distance of 1.38 in. (3.5 cm) downstream of the venturi throat. The upstream boundary was largely established by the normal shock and the sudden expansion of the flow at the pre-

Table I – Comparison of engine and rig acoustic features.

Feature	Engine	Rig
Combustor Volume per Injector (in.^{3}/cc)	113 / 1851	108 / 1770
Combustor Length (in./cm)	8.5 / 21.3	8.5 / 21.3
Shroud Volume per Injector (in.^{3} /cc)	129.3 / 2119	103.4 / 1695
Nominal Shroud Height (in./cm)	1.2 / 3.0	0.80 / 2.0
Diffuser length (in./cm)	2.7 / 6.9	2.7 / 6.9
Pre-diffuser Length (in./cm)	3.9 / 9.9	3.9 / 9.9

diffuser dump. The downstream boundary was defined by using a choked exhaust nozzle at the station occupied by the first turbine inlet vane.

D. *Reproduction of the air flow distribution, pressure drops and flow damping characteristics*
The pressure drops and airflow splits used in the engine were duplicated. That is, the fractions of air used for liner cooling and for primary and dilution air were reproduced. Designing for equivalent damping is important to achieving similar instability amplitudes between the test rig and the engine. The resistive damping of the system was maintained by replicating the system's pressure drops. Reproducing the splits between the different air flows replicates the distribution of stoichiometry and heat release rate within the combustor. The shroud height (distance between combustor liner and pressure vessel wall) was also preserved in order to preserve the shroud air velocity.

E. *Design for testing at engine operating conditions*
The instability observed in the engine occurred over a range of test conditions. A single "Evaluation Point" was chosen at 200-psia (1.2 MPa) combustor pressure, an entrance temperature of 771°F (684K), and combustor fuel-air ratio of approximately 0.03. This mid-power point on the engine operating curve did not correspond to the highest-amplitude pressure oscillations, but was the maximum power level achievable given the facility limitations. All analyses were conducted at these conditions. Operating at reduced conditions with full-scale hardware can change the operating characteristics of the components (pressure drops, atomization, etc.).

F. *Design acoustic flexibility into the rig*
In order to minimize risk, the rig was designed so that the parameters that affect the driving acoustics could be varied. Specifically, a design option was desired which would permit the inlet plenum upstream of the combustor to be tuned to provide a 500-Hz class resonance. In addition to providing flexibility for the rig acoustics, this also provided an additional case for which modeling techniques could be validated.

The final consideration was whether to utilize an apparatus with a simple cylindrical cross-section burner or an apparatus having a cross-section representative of 1/24 of the 24-nozzle engine burner – i.e., a 'single sector' burner. A circular cross-section was employed, as this represented the lower-cost, higher-strength approach. The number and size of the combustion and dilution air holes was adjusted to provide proper penetration of these air jets.

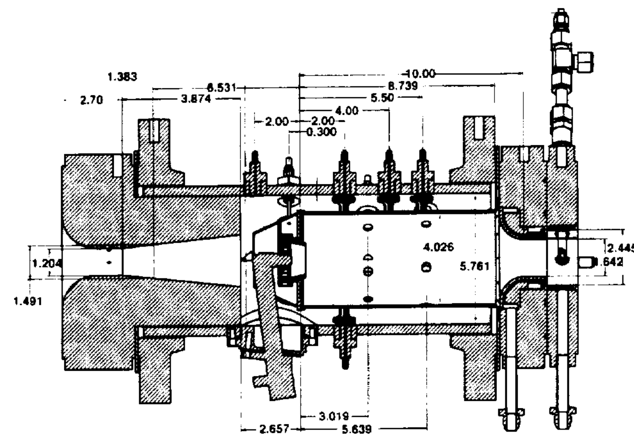

Figure 5. The combustor test section assembly. Dimensions are in inches.

The configuration of the test section is illustrated in Fig. 5. Provisions for high-response pressure transducers and for gas sampling (not reported herein) were incorporated.

Three transducer bosses, equally spaced around the circumference, were located in the primary combustion zone. One was located in the secondary zone, and one in the dilution zone. Floating seals on the liner captured extension tubes attached to the pressure-vessel-mounted transducers such that the pressures at the inside liner surface could be recorded.

Bosses for shroud flow pressure measurements were provided at the location of the liner primary and dilution holes. Bosses for diffuser pressure measurements, upstream of the combustor, were also provided

PCB piezo-electric pressure transducers (P/N 124A21) were selected for this application based on demonstrated ability to withstand the severe environment encountered in the combustor and pre-diffuser (high temperature and pressure). Originally developed for measuring combustion instability in liquid rockets, they are capable of measuring ±250 psi. pressure fluctuations at frequencies between 0.5 Hz and 10 kHz. Satisfactory durability was achieved by use of an integral water-cooled mounting fixture that maintained an acceptable temperature around the sensor. The liner pressure sensors communicated with the combustor through a 0.062 in.

(1.6 mm)-diameter, 0.83 in.(2.1 cm) -long sensing tube. A 1000 psia nitrogen supply was used to purge the tube – the amount of purge flow rate was negligible. The ¼-wave resonant frequency of the cavity within this tube was far above the frequency range of interest in this experiment. Analog data were low-pass filtered at 2 kHz and digitally sampled at 5 kHz using a simultaneous sample-hold data acquisition system.

Analysis of Baseline Single-Nozzle Rig Acoustics

The baseline single-nozzle combustor rig design was established to preserve the axial lengths and cross-sectional areas of the engine configuration relative to a single nozzle. The area vs. axial position distribution was maintained approximately the same (ref. Fig. 2), but some variation existed due to differences in engine hardware and the axisymetric hardware to be used in the single-nozzle combustor. Airflow splits and pressure losses – swirler, bulkhead, liner, primary and dilution jets were also preserved by design. The inlet and exit of the rig were choked to acoustically isolate the system. The Euler models included inlet and exit plenums upstream and downstream of the choke points to allow constant total pressure and constant static pressure to be specified, respectively, as boundary conditions to be applied to the Euler code domain.

Quasi-1D Euler calculations were conducted for the baseline rig configuration at the evaluation point operating condition: 771°F (684 K), 200 psia (1.2 MPa). Swept-sine forcing over the frequency range from 100 to 800 Hz was applied to the heat release. The resulting power spectrum of the pressure response is shown in Fig. 6, indicating the presence of resonances at ~115 Hz and ~575 Hz. The level of forcing employed in the analysis is arbitrary, and within the linear response range, so that no significance should be attached to the absolute levels of the ordinates in Figures 3 through 9.

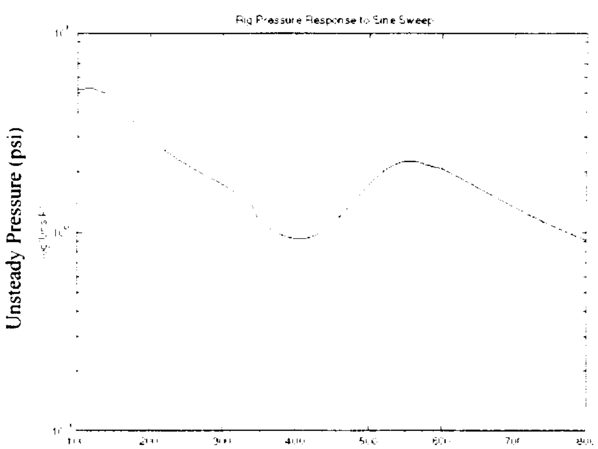

Figure 6. Computed power spectrum of combustor pressure at x = 3.0 in. for the baseline rig configuration. Quasi-1D Euler code results for 100-800 Hz swept-sine forcing of heat release.

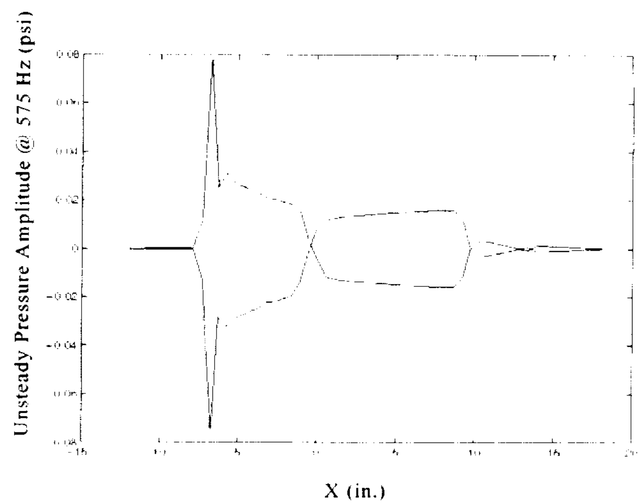

Figure 7. Predicted pressure mode shape for the 575 Hz mode for the baseline rig configuration at evaluation point conditions.

Further analysis of the mode shapes associated with these resonances revealed that the low frequency 115 Hz mode was a first-order longitudinal mode where the diffuser and combustor were in phase. The primary mode of interest was the 575 Hz mode since the observed instability frequency in the engine was 525 Hz. The pressure mode shape is shown in Fig. 7. The 575 Hz mode was essentially a half-wave longitudinal mode considering closed/closed acoustic boundary conditions from diffuser inlet to combustor exit. A pressure node appeared to occur at the air swirler/ fuel injector location. The pressure in the diffuser was 180 deg. out of phase from the pressure in the combustor. Note there was some activity downstream of the combustor exit, but calculations performed with varying exit plenum length did not indicate significant changes in the resonant frequency.

The main conclusion drawn from the acoustic analyses was that the single-nozzle combustor rig configuration would have a longitudinal acoustic resonance at about 575 Hz that is very similar to the mode observed in engine data and predicted by Euler analysis of the engine configuration.

Analysis of Extended Single-Nozzle Rig Acoustics

The quasi-1D Euler analysis was also used to design acoustic modifications to the baseline rig. As mentioned earlier, these modifications were desired to allow the acoustic characteristics of the rig to be tuned. In particular, flexibility in the "acoustic length" of the rig was achieved by increasing the diffuser length (the distance between the prediffuser dump and the combustor bulkhead) by fractions of the wavelength of the 575Hz mode (i.e., ¼ and ½ wavelengths). For nominal operating conditions, each ¼-wave corresponded to approximately 8.5 inches (24.2 cm) of diffuser length. The analysis showed that increasing the diffuser length by 19 in. (48.3 cm.) could also result in a 535-Hz system mode. In the experiment, this extended configuration was implemented using a cylindrical pipe spool section with an inside diameter of 6 in. (15.2cm). The pressure spectrum of the combustor pressure response to random forcing (as calculated by the Euler analysis) with the extended section upstream is shown in Figure 8. The dominant acoustic resonance appeared at 300 Hz, with modes also present at 535, 800 and 2000 Hz. The mode shape for 300 Hz is shown in Figure 9, and relative to the baseline configuration, the pressure node moved upstream of the swirler and into the inlet plenum.

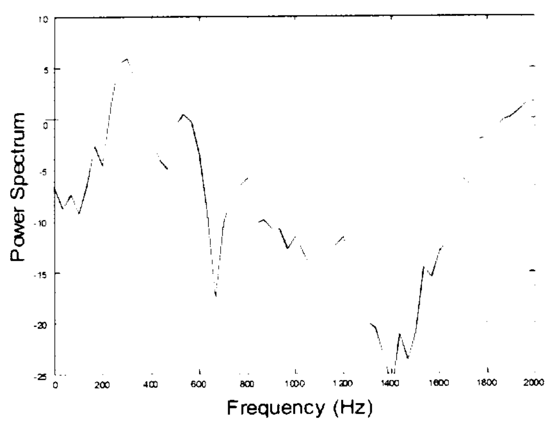

Figure 8. Computed power spectrum of combustor pressure for extended rig configuration, showing dominant mode at ~300 Hz.

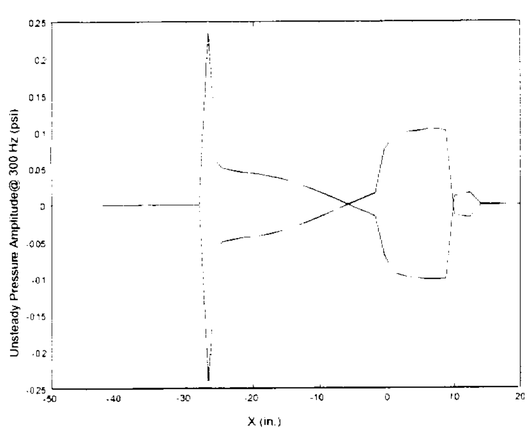

Figure 9. Predicted pressure mode shape for 300 Hz mode in extended rig configuration.

EXPERIMENTAL RESULTS

The operating conditions of the combustor could be completely described by the following parameters: diffuser air pressure (P3), diffuser air temperature (T3) and combustor fuel/air ratio (f/a). Values for each of these parameters were chosen to correspond to three different engine operating conditions. These are shown in Table 2. The fuel/air ratio referred to is that estimated at the exit of the combustor and accounted for all of the air flowing into the combustor through the air swirler, primary and dilution holes and liner/bulkhead cooling passages. It was not possible to vary the test parameters independently because of the choked, fixed-area combustor exit.

Table II – Test conditions corresponding to engine operating points. Evaluation-point conditions are in italics.

Inlet Air Pressure, P3 (psia/MPa)	Inlet Air Temperature, T3 (°F / K)	Fuel/Air Ratio
70 / 0.48	500 / 533	0.016
110 / 0.76	600 / 589	0.024
175 / 1.21	*771 / 684*	*0.030*

Results for Baseline Rig Configuration

For the evaluation point operating conditions, an instability was observed at a frequency of 566 Hz (see Fig. 10). The amplitude of this mode at these conditions was +/- 0.39 psi (2.7 kPa). The unsteady pressure results presented here are from the transducer located at 2.0 in. (5.1 cm.) downstream of the combustor bulkhead. The amplitude of the instability increased with increasing fuel/air ratio for fixed P3 and T3. At higher fuel/air ratios, the overall RMS pressure fluctuations were dominated by this single tone. There was significant noise generated in the 100-300 Hz range, although none of it was particularly coherent.

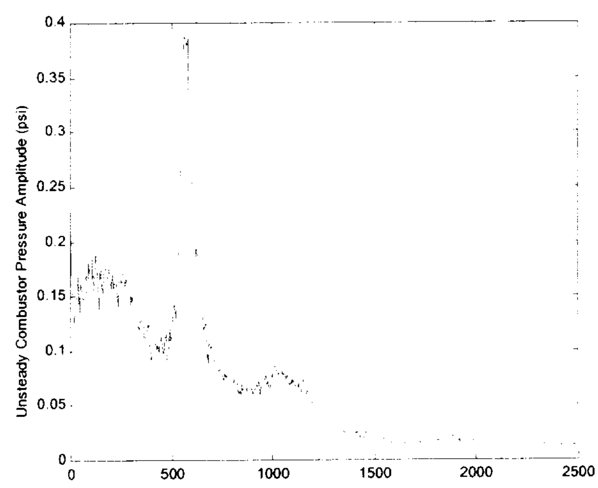

Figure 10. Measured power spectrum of unsteady combustor pressure at x = 2 in. for the baseline rig configuration at Evaluation Point operating conditions, showing resonance at 566 Hz, with an amplitude of 0.39 psi (0.78 psi p-p).

Figure 11 shows the spatial distribution of the unsteady pressure at three locations within the combustor and one location in the diffuser region upstream. Within the combustor, there was no phase difference between measurements at different axial stations, and only small differences in amplitude. Significant 566 Hz signal was also apparent upstream of the combustor, which lagged the combustor pressure by 92 degrees in phase and was smaller in amplitude by a factor of 2. There were no phase or magnitude differences (at 566 Hz) between pressure measurements at equivalent axial, but differing circumferential stations, consistent with a longitudinal acoustic mode. The unsteady pressure in the shroud, just outside the dilution holes was a factor of 2 smaller than that in the combustor and lagged the combustor pressure by approximately 40 degrees.

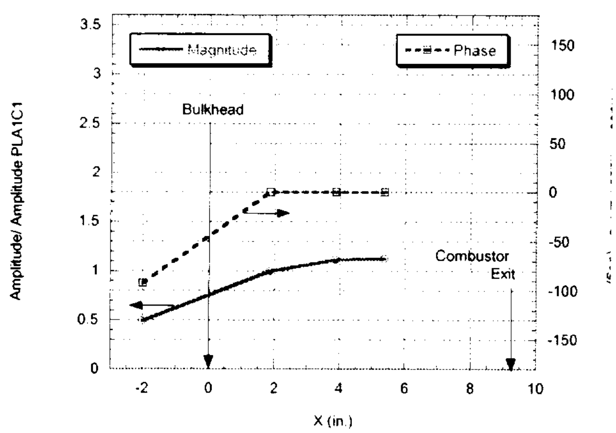

Figure 11. Measured distribution of 566 Hz mode for the baseline rig configuration, showing magnitude and phase referenced to pressure measurement PLA1C1 at x = 2.0 inches downstream of the combustor bulkhead.

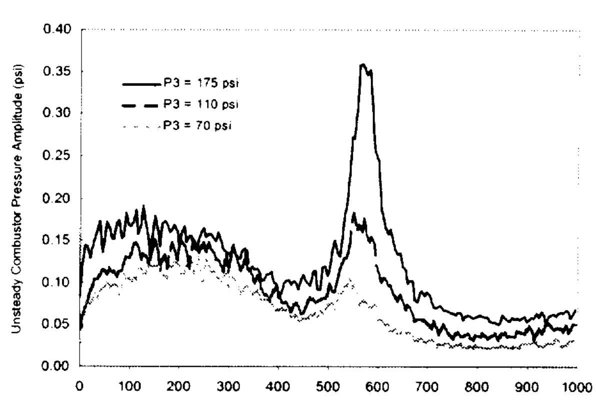

Figure 12. Power spectra of unsteady combustor pressure for the baseline rig configuration at three operating conditions corresponding to those in Table 2, showing decreasing amplitude of 566 Hz mode with decreasing power level.

This mode was also observed at the other two, lower-power, operating conditions, although at smaller amplitudes and lower frequencies, as shown in Fig. 12.

Results for Extended Rig Configuration

This configuration used two 9.5-inch spool sections (between the upstream venturi insert and the flange that captured it) to increase the length between the venturi throat and the combustor bulkhead by 19.25 inches relative to the baseline configuration.

The spectrum of the unsteady combustor pressure is shown in Figure 13 for the Evaluation Point operating conditions. A high-amplitude (5.4 psi) instability at a frequency of 273 Hz was evident, along with higher-order harmonics at approximately 550 Hz and 820 Hz. In contrast with the spectra observed with the baseline configuration, the peaks here were narrow and very coherent.

The unsteady pressure distribution for this configuration is shown in Figure 14 and, within the combustor, appears similar to that seen in the baseline configuration for the "566 Hz" mode. The unsteady pressure was essentially uniform and in-phase within the combustor. For this case, however the unsteady pressure in the diffuser led the combustor pressure by 30 degrees. Its amplitude was 2.9 times lower than that observed in the combustor. Upon inspection of the circumferential array of transducers within the combustor, there was no indication of a tangential mode. All of the combustor unsteady pressure measurements were in-phase and of nearly-equal amplitude.

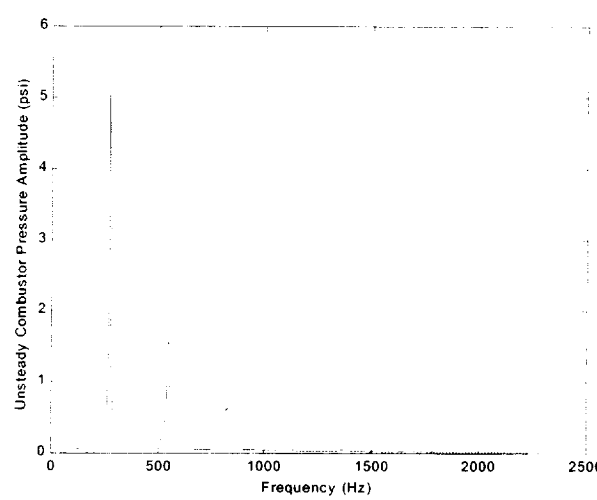

Figure 13. Power spectrum of unsteady combustor pressure at Evaluation Point operating conditions for the extended diffuser configuration

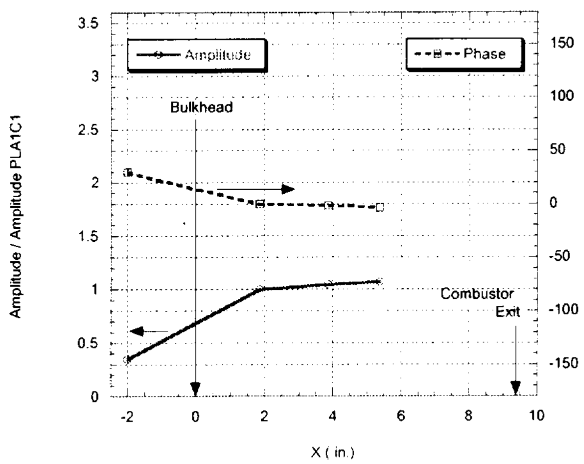

Figure 14. Measured distribution of 273 Hz mode in the extended configuration, showing magnitude and phase referenced to pressure measurement PLA1C1 at x =2.0 inches downstream of the combustor bulkhead.

ANALYSIS OF RESULTS

Comparison with Analytical Results: Baseline Combustor

The experimental results can be compared to the analytical results by referencing Fig. 6, which shows the predicted pressure spectrum, and Fig. 10, which shows the measured pressure spectrum. Recall the Euler code model predicted broad acoustic resonances at about 575 Hz and 115 Hz. In the experiment, a broad instability centered near 566 Hz was observed, and there was some incoherent activity indicated near 100-200 Hz. Thus, the agreement appears to be good. The mode shape measured in the experiment was of limited spatial resolution and showed little spatial variation of unsteady pressure amplitude or phase within the combustor chamber itself for the 566 Hz mode (ref. Fig. 11). This was consistent with the mode shape of the 575 Hz mode predicted by the Euler code (ref. Fig. 7). Note both results did indicate a slight decrease in amplitude towards the upstream end of the combustion chamber. The Euler code prediction indicated the unsteady pressure in the diffuser upstream of the combustor would be 180° out-of-phase with the combustor pressure. The experimental results indicated a significant phase shift in the diffuser section, lagging the combustor pressure by about 90 degrees at 566 Hz. This discrepancy is likely associated with the 1-D limitations of the model. For example, it is expected that some level of coupling to the outer shroud passage would occur which is also coupled to the combustor via the air mixing holes. Therefore, some transition of the phase from in-phase with the combustor outside the mixing holes to out-of-phase in the diffuser section is expected in the 3-D problem. The result could be a phase relation in the diffuser section between 0 and 180 degrees.

Note that, because the Euler code is essentially an acoustic calculation, it is fundamentally limited in its ability to calculate the amplitude of the pressure oscillations without the addition of a combustion / acoustic coupling model. In calculations for the engine using a constant relative forcing level, the Euler code indicated that both the frequency and amplitude of the instability should increase with increasing engine power level. This trend was validated with engine data and was also reproduced in the single-nozzle experiment (ref. Fig. 1 and Fig. 12). It is also encouraging that the damping mechanisms present in the calculations produced a broad peak at 575 Hz, much like that seen in the experiment (see Fig. 12).

Comparison with Analytical Results: Extended Combustor

Both the Euler analyses (Fig. 8) and the experimental results (Fig. 13) exhibited a dominant peak near 300 Hz for the extended configuration. The spatial distribution of unsteady pressure measured in the experiment (Fig. 14) showed no variation of unsteady pressure amplitude or phase within the combustor itself for the 273 Hz mode. This was consistent with the predicted mode shape of the 300 Hz mode (Fig. 9). The Euler code predicted that this mode would be a ½-wave longitudinal mode with a pressure node at approximately 5.0 inches upstream of the swirler/bulkhead location. For this mode shape, the unsteady pressure at the diffuser measurement station (X = -2.0 in.) would be in phase with the combustor pressure. This prediction was validated by the experimental results, which showed that the diffuser pressure led the combustor pressure by only 30 degrees at 273 Hz, making them nearly in-phase with each other. The mode shape results are consistent with the idea that the effect of the extended diffuser was to "stretch" the mode observed in the Baseline Configuration over a longer length, causing a reduction in its frequency and a shift in the location of the pressure node relative to the bulkhead.

Comparison with Engine Data

Figure 15 shows a comparison between the fluctuating pressure spectrum in the engine and the baseline single-nozzle combustor at comparable operating conditions. Both data sets were acquired over 10 seconds, and were processed using the same techniques. The frequency of the "target" mode was reproduced within 12%. The amplitude of this mode was matched within 3%. The spectral peak was significantly narrower in the engine data, indicating a more coherent instability. The single-nozzle combustor also exhibited a higher overall level of noise in the signal, especially at frequencies below 350 Hz.

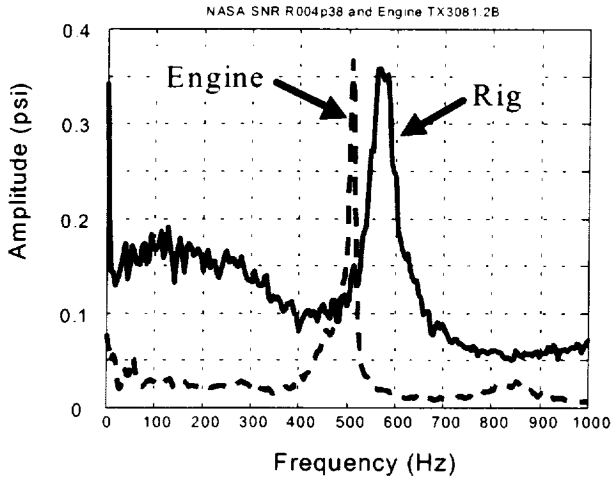

Figure 15. Comparison of engine and baseline combustor rig pressure spectra for Evaluation-Point operation.

CONCLUSIONS AND RECOMMENDATIONS

A methodology for replicating longitudinal combustion instabilities observed in an aircraft engine in a single-nozzle test rig was successfully demonstrated. The experiment reproduced the frequency of the engine instability within 12% and its amplitude within 3%.

Necessarily, the replication procedure must use both predictions from analytical tools and engineering judgements based on prior combustion dynamics studies. A relatively simple, quasi-one-dimensional Euler analysis is satisfactory for the prediction of the dynamics of longitudinal instabilities in geometrically complex burners.

The one-dimensional analytical acoustic tools applied in this program predicted the basic acoustic frequencies of the engine, the rig and an acoustically- modified version of the rig within about 10%, and supported a methodology to define a test rig with specific acoustic frequency characteristics. The technique was capable of predicting the dominant longitudinal mode and its frequency for both rig configurations. However, because the tool is a one-dimensional analysis, it cannot capture all the dynamic features of this combustor. For example, as reported, it did not quantitatively predict the phase relationship between the combustor and diffuser. The development of an analytical tool would include multi-dimensional capability to either identify other modes or include the influence of parallel acoustic paths (e.g., shroud) is recommended.

An extension of these tools to design sub-scale experiments in which instabilities associated with tangential acoustic modes would also be useful. Inclusion of acoustic-heat release coupling would also increase the tool's utility. Acoustic-heat release coupling models could provide a capability for further reductions in the scale of the experiment, in such parameters as geometric size, flow rates and operating pressure.

In summary, a methodology for design of laboratory combustors, which reproduce combustion instabilities observed in aircraft engine combustors, has been demonstrated. A realistic platform for the development and validation of active combustion instability control systems was constructed, and will be utilized in subsequent programs.

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Combustion instabilities can lead to increased development time and cost for aeroengine gas turbines. This problem has been evident in the development of very-low emissions stationary gas turbines, and will likely be encountered in the newer, more aggressive aeroengine designs. In order to minimize development time and cost, it is imperative that potential combustion dynamics issues be resolved using analyses and smaller-scale experimentation. This paper discusses a methodology through which a problem in a full-scale engine was replicated in a single-nozzle laboratory combustor. Specifically, this approach is valid for longitudinal and "bulk" mode combustion instabilities. An explanation and partial validation of the acoustic analyses that were used to achieve this replication are also included. This approach yields a testbed for the diagnosis of combustion dynamics problems and for their solution through passive and active control techniques.

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